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**The Fluids And Combustion Facility Combustion  
Integrated Rack And The Multi-User Droplet  
Combustion Apparatus: Microgravity Combustion  
Science Using Modular Multi-User Hardware**

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# The Fluids And Combustion Facility Combustion Integrated Rack And The Multi-User Droplet Combustion Apparatus: Microgravity Combustion Science Using Modular Multi-User Hardware

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## Abstract

The Fluids and Combustion Facility (FCF) is a multi-rack payload planned for the International Space Station (ISS) that will enable the study of fluid physics and combustion science in a microgravity environment. The Combustion Integrated Rack (CIR) is one of two International Standard Payload Racks of the FCF and is being designed primarily to support combustion science experiments. The Multi-user Droplet Combustion Apparatus (MDCA) is a multi-user apparatus designed to accommodate four different droplet combustion science experiments and is the first payload for CIR. The CIR will function independently until the later launch of the Fluids Integrated Rack component of the FCF. This paper provides an overview of the capabilities and the development status of the CIR and MDCA.

## Introduction

The ISS allows microgravity research to be conducted in space for periods of months or longer in the U.S. Lab Module Destiny (Fig. 1). A primary facility for microgravity research on-board the ISS will be the Fluids and Combustion Facility (FCF). The FCF is being developed by the NASA Glenn Research Center in Cleveland, Ohio<sup>1,3,5</sup>. The FCF will support microgravity combustion and fluid physics research.

The FCF consists of a Flight Segment and a Ground Segment. The FCF Ground Segment includes ground racks and equipment to be used for experiment development, astronaut training, telepresence operations and other essential Earth-based functions. The FCF Flight Segment comprises two on-orbit racks that will be located inside the U.S. Laboratory Destiny. These racks are the Fluids Integrated Rack (FIR), and the Combustion Integrated Rack (CIR)<sup>4,7</sup>.

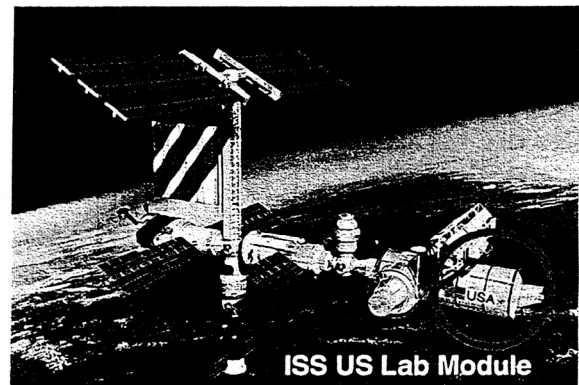


Figure 1. The International Space Station

The CIR will provide combustion research opportunities in extended microgravity conditions on board the ISS. Along with the MDCA, the CIR will be the first FCF rack deployed to the Space Station on Utilization and Logistics Flight #2 (ULF-2). Initially, the CIR will operate independently. Once the FIR is deployed to ISS, the CIR will function together with it to provide a complete on-orbit research facility capable of meeting NASA Office of Biological and Physical Research Program objectives for sustained, systematic microgravity combustion research for the lifetime of the ISS (i.e., a minimum of ten years following ISS assembly complete).

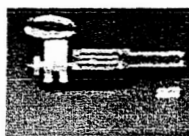
The MDCA<sup>8,9</sup> is the initial payload in the CIR. It contains the hardware and software required to conduct unique droplet combustion experiments in microgravity. It consists of a Chamber Insert Assembly, an Avionics Package, and a suite of diagnostics. The MDCA is currently scheduled to be on-orbit for 14 months, and will perform four different droplet combustion experiments.

## CIR System Description

The basic concept behind the CIR is that it provides up to 90% of the required hardware to perform a majority of future microgravity combustion experiments on board the ISS. The remaining 10+%

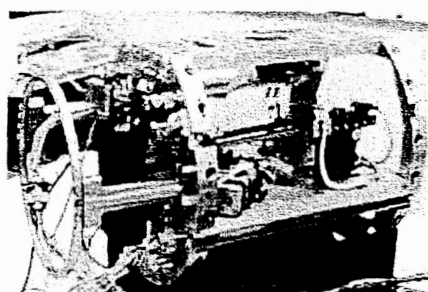
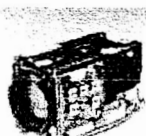
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## CIR/MDCA Integrated Configuration



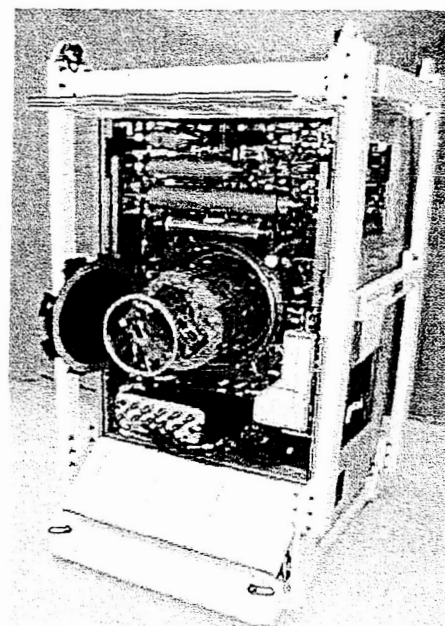
### PI Specific Hardware

- Unique PI fuels
- Specialty diagnostics
- Unique hardware components



### MDCA Experiment Insert

- Platform for droplet:
  - Dispensing
  - deploying
  - Ignition
- Unique science requirements



### Combustion Integrated Rack

- Structural Support & Power
- Common Diagnostics and Illumination
- Environmental Control
- Data Processing/Distribution
- Fluids Control/Distribution
- Combustion Containment

Figure 2. The CIR and MDCA

of hardware will be provided by the PI hardware development teams. Figure 2 shows the CIR Engineering model with the MDCA Functional unit. PI-specific hardware, such as MDCA will be launched separately from the CIR and integrated with the CIR on orbit. A significant amount of PI hardware is expected to be reused for follow-on experiments.

The CIR consists of the following major subsystems and components;

- International Standard Payload Rack (-4 ISPR)
- Passive Rack Isolation Subsystem (PaRIS)
- Optics Bench on slides that tilts out of the ISPR
- Combustion Chamber with replaceable windows
- Fuel and Oxidizer Management Assembly (FOMA), including a gas supply package, exhaust vent system and gas chromatograph.
- Modular, replaceable Science Diagnostics
- Environmental Control Subsystems, including water thermal control, air thermal control, fire detection/suppression and gas interfaces
- Electrical Power Subsystem
- Avionics Subsystems, including the CIR main computer (Input/Output Package), image processing and storage units, FOMA control unit

and Station Support Computer.

- Flight and Ground Software
- Interfaces for replaceable, Experiment-Specific Equipment

The CIR design allows different experiment packages within the combustion chamber to be removed, replaced or upgraded. Modular diagnostics are mounted on the optics bench and are easily repositioned.

The CIR and associated ground systems will offer the Principal Investigators the opportunity to participate in the conduct of their experiment on-board the ISS through remote operation and observation. Once a test point has been completed, the PI can assess the results and provide information for changes to the test matrix. Ground systems will also enable scientists to interact with researchers at other locations.

The Subsystems common to all FCF Racks are described elsewhere<sup>3,4,6</sup>.

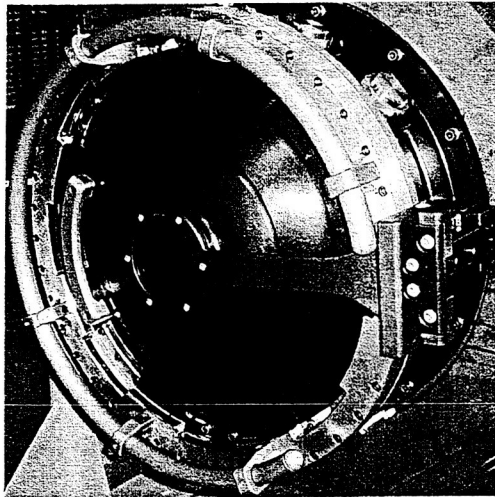
## CIR Specific Subsystems

### Combustion Chamber

The CIR combustion chamber provides structural support and on orbit access for installation and removal of a combustion experiment insert with maximum dimensions of 60.0 cm long and 39.6 cm in diameter (Fig. 3). The Chamber Insert contains all of the experiment hardware such as fuel, igniters nozzles etc. The chamber is a cylindrical vessel with domed end caps that is centrally mounted to the optics bench. It has a one-hundred (100) liter free internal volume, an internal diameter of 40.0 cm and a length of 90.0 cm. A combustion experiment insert slides into the chamber from the front and is locked into position.

### Combustion Chamber Features:

- Provides structural support for the PI Hardware with on orbit access for installation and removal.
- Operates at pressures ranging from 0.02 to 3 atmospheres and has a maximum design pressure of 120 psig (approximately 8 atmospheres)



- The Chamber door is an 8 tab breech lock hinged front lid. No tools required to open
- The 8 windows are removable from inside the chamber for service and change-out. No tools required for replacement
- Baseline window material is sapphire
- Interface Resource Ring provides:
  - 4 electrical connectors
  - Inlet & outlet port for water cooling
  - 2 thermistors, 2 pressure transducers, 1 pressure switch
  - Nitrogen supply
  - Gaseous fuel/premixed
  - Partial pressure mixer
  - High pressure supply
  - GC Sampling
  - Exhaust Vent Port

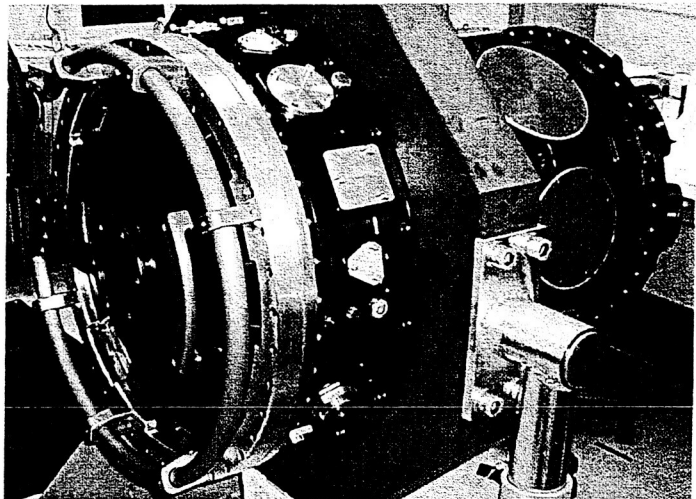


Figure 3: The CIR Engineering Model combustion chamber

### Passive Rack Isolation Subsystem

The CIR ISPR will be outfitted with an Passive Rack Isolation System (PaRIS) to isolate it from ISS vibrations. The PaRIS is a passive rack vibration isolation system intended for use in the USL. By suspending the integrated payload rack from the ISS module structure using passive dampers, it will attenuate vibratory accelerations above 1 Hz to the CIR. The PaRIS is composed of the following:

- Upper isolation strut adapter/interface assembly
- Upper lock-down/snubber assembly
- Lower isolation adapter/interface assembly

- Lower lock-down/snubber assembly
- Utility umbilical assemblies
- Passive isolation units
- Installation/adjustment/maintenance hardware

The combination of the CIR and PaRIS provides vibration isolation in both dynamic load path directions (i.e. attenuating vibrations imposed on the rack by the ISS vehicle as well as attenuating vibrations induced on the ISS vehicle by the rack) without consuming any ISS resources. The utility umbilical assembly provides a low bias force and spring rate connection between the module structure



and the payload rack structure for utility pass-through.

### Fuel and Oxidizer Management Assembly

A Fuel and Oxidizer Management Assembly (FOMA) provides the ability to safely deliver gaseous fuels, diluents and oxidizers to experiments in the CIR combustion chamber. The FOMA also samples the chamber environment using a gas chromatograph and controls the venting of chamber gases, at acceptable concentration levels, to the ISS Vacuum Exhaust System (VES). The FOMA consists of a gas delivery package, an exhaust vent package and a gas chromatograph (GC). The Engineering Model FOMA is pictured on the front of the optics bench in Figure 4.

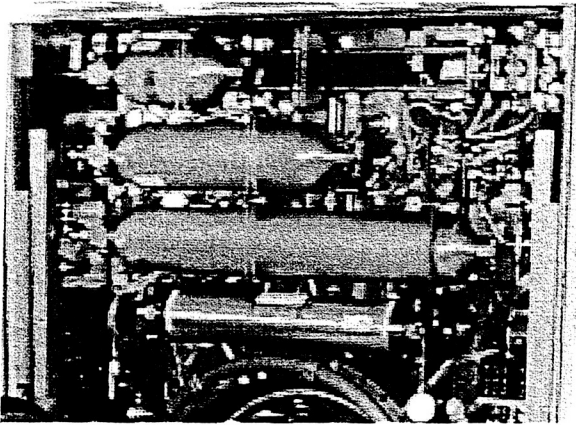


Figure 4. The FOMA System

#### Gas Delivery Package

The Gas Delivery Package (GDP) consists of gas supply bottles and the necessary hardware and instrumentation to regulate and deliver up to three (3) different gases to the combustion chamber. Gas bottles are located in the CIR on the front of the optics bench. Up to four gas bottles can be installed simultaneously in the CIR. The bottles are mounted using quick disconnects for rapid replacement by the crew, as required for each experiment. Gas bottles installed in the CIR are for the active experiment only. Additional bottles required on-orbit are stowed.

#### Features of the Gas Delivery Package:

- Gas is delivered through 1.0, 2.25, and 3.8 liter bottles
- Oxidizers bottles:
  - 1.0 liter up to 80% O<sub>2</sub>
  - 2.25 liter up to 50% O<sub>2</sub>

- 3.8 liter up to 30% O<sub>2</sub>
- Quick disconnects used for easy attachment to manifolds
- Provides chamber environment via partial pressure or dynamic gas blending
- Maximum oxidizer flow rates
  - 30 slm per manifold
  - 90 slm total
- Maximum fuel flow rate 2 slm

#### Exhaust Vent Package

The Exhaust Vent Package (EVP) connects the combustion chamber with the ISS vacuum exhaust. The EVP includes an adsorber cartridge and a recirculation loop to condition the chamber gas environment for the next test point or to convert post-combustion gases into species that are acceptable to vent. Chamber gases are pumped through the recirculation loop using two magnetically-coupled recirculation pumps mounted on the rear end cap of the combustion chamber at a maximum re-circulation flow rate is 20 SLM.

#### Features of the Exhaust Vent Package:

- Removes unacceptable species including water vapor, and particulates from the combustion event to allowable limits
- Manifolds located on front and back of bench
- Measures oxygen concentrations and dew point levels to assure ISS VES compliance
- Adsorber cartridges are customized to experiment requirements (e.g. Lithium Hydroxide, Activated Carbon, Silica Gel, and Molecular Sieve)
- Mass flow controller used to regulate vented gas

#### Gas Chromatograph

The combustion chamber environment can be sampled using a Gas Chromatograph (GC). The GC is a repackaged commercial unit with three (3) independent separation columns and sensors capable of utilizing different carrier gases, such as Helium, Hydrogen, Nitrogen, and Argon. The 500 mL, 1,800 psia carrier gas bottles are sized to minimize bottle changeouts by the crew. The GC can accommodate up to four (4), 50 mL, 1,800 psia calibration gases. The GC lower detection limit is 100 ppm (depending on the compound) with an expected accuracy of  $\pm 2\%$ .

### Science Diagnostics

Science diagnostics are used in the CIR to image combustion experiments. Diagnostics assemblies are mounted on the rear of the CIR optics bench at one of the eight universal mounting locations (UML)

around the chamber and view the flame through optical windows in the chamber. A removeable latch mechanism, compatible with all science diagnostics packages, is used to attach and remove diagnostic assemblies from the optics bench.

Science diagnostic packages are constructed from modular optical components connected at standard interfaces to enable easy, on-orbit diagnostics package reconfiguration. Each package in the CIR consists of an Imaging Module, Optics Modules and a Diagnostics Control Module (DCM).

Five standard diagnostic packages, constructed from these modular elements are planned as initial diagnostic capabilities for the CIR (Fig. 15). These are a High Bit Depth/Multispectral Imaging Package (HiBMs), a High Frame Rate/High Resolution (HFR/HR) Package, two (2) Low Light Level Camera Packages, and an Illumination Package.

#### *High Bit Depth/Multi-Spectral Imaging Package*

The HiBMs package consists of a spectrally filtered, telecentric optical system and a high resolution, 12-bit output digital camera. The HiBMs Package can be used to measure soot volume fraction and soot temperature of soot-producing flames. It can also be used for shadowgraph measurements by adjusting the lens aperture and filter.

Features of the HiBMs:

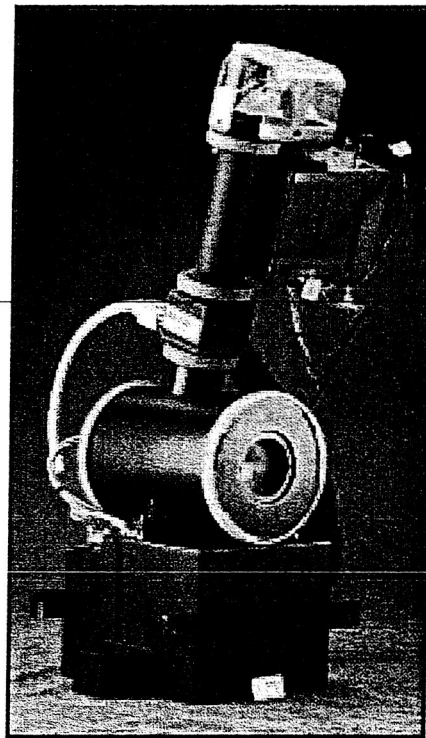
- Numerical Aperture: 0.005 to 0.02
  - Focus at chamber centerline
  - Field of View: 50 mm square or 80 mm diameter
  - Resolution: 10 lp/mm maximum (0.05 mm)
- Liquid Crystal Tunable Filter (LCTF)
  - 10 nm FWHM bandpass
  - 650-1050 nm spectral range
  - 1 nm spectral resolution
  - 100 ms switching time between states
- Programmable frame rate (7.5, 15 or 30 fps) and exposure time

#### *High Frame Rate/High Resolution Package*

The High Frame Rate/High Resolution (HFR/HR) Diagnostics Package (Fig. 5) provides programmable frame rates and high optical resolution performance. It consists of a telecentric optical system, a trombone prism assembly, a pointing mirror assembly, digital camera and associated control electronics. The HFR/HR Package is capable of automatically tracking an object within the total field of view, while maintaining a sharp focus over a full object distance displacement range of 30 mm.

Features of the HFR/HR:

- Automated Tracking - Capable of steering a 9x9 mm Instantaneous FOV (IFOV) over a total 46 mm dia. total FOV truncated to 37 mm horizontally & vertically
- 10mm/s maximum tracking speed
- Automated focus over 30mm object depth; 5mm/s focus speed; telecentric
- Package may be programmed to sequentially operate in the 2 alternate modes
  - High Resolution Mode: 1024x1024 pixels at frame rates of 7.5, 15, or 30 fps
  - High Frame Rate Mode: 512x512 pixels at programmable frame rates of 60 or 110 fps
- Resolution is 20 lp/mm at 50% contrast in HR mode (0.009 mm at Nyquist limit)
- Event trigger capability



**Figure 5. High Frame Rate/High Resolution Diagnostics Package**

#### *Low Light Level Packages (UV and IR)*

The Low Light Level (LLL) packages provide images of events or objects at low radiance levels. A LLL package consists of a digital monochrome camera coupled to an intensifier with fast numerical aperture optics and provision for spectral filtering of the transmitted illumination.

LLL-UV Features:

- Optical System
  - FOV: 42 and 100 mm square

- Resolution: wide field: 2.8 lp/mm (0.18 mm); narrow field: 6.7 lp/mm (0.075 mm)
- Provision for manually inserted filters. Providing 310 nm filter with a 10 nm FWHM bandwidth.
- Manual iris and focus
- Camera
  - Spectral range: 220-850 nm
  - Sensitivity:  $5 \times 10^{-8}$  ft. candles binned
  - Intensifier: Gen II
  - Frame rate 60 fps

#### LLL-IR Features

- Optical System Parameters
  - FOV: 45 to 180 mm square
  - 2X motorized zoom capability, and two objective lenses.
  - Resolution: wide field 3.4 lp/mm (0.15 mm); narrow field: 6.8 lp/mm (0.07 mm)
  - Motorized focus and iris
  - Accepts standard bandpass filters. Filters are removable for broadband imaging capability
- Camera
  - 400-900 nm (IR shifted)
  - Sensitivity:  $5 \times 10^{-8}$  ft-candles binned
  - Intensifier: Gen III Ultra

#### *Illumination Package*

The Illumination Package provides an illumination source to the chamber and is used in conjunction with diagnostics packages that require backlight illumination. It consists of a collimated optical system, a Fixed Mirror Module and an Illumination Control Module. The illumination source is a laser diode array that can be used to provide monochromatic background illumination

#### Features:

90 mm diameter collimated beam

- 50% illumination field uniformity
- 7.6 milliradians divergence
- Peak wavelength: 660nm with a spectral bandwidth of 7nm at the 50%points

Can be synchronized with the imaging packages

#### CIR Status

Engineering model hardware for the CIR is essentially complete and is finishing Rack-level engineering model testing. A Critical Design Review (CDR) of the CIR was held in May 2002 and The

flight hardware is currently being built, with the rack level testing to start in August 2003.

### The Multi-User Droplet Combustion

#### Apparatus

The Multi-user Droplet Combustion Apparatus (MDCA) is a multi-user facility designed to accommodate four different droplet combustion science experiments. The MDCA will conduct experiments using the Combustion Integrated Rack (CIR). The MDCA, in conjunction with the CIR, will allow for cost effective extended access to the microgravity environment, not possible on previous space flights. It is currently in the Engineering Model build phase.

The MDCA contains the hardware and software required to conduct unique droplet combustion experiments in space. It consists of a Chamber Insert Assembly (CIA), an Avionics Package, and multiple diagnostics. Its modular approach permits on-orbit changes for accommodating different fuels, fuel flow rates, soot sampling mechanisms, and varying droplet support and translation mechanisms to accommodate multiple investigations. Unique diagnostic measurement capabilities for each investigation are also provided.

Single combustible fuel droplets of varying sizes, freely deployed or supported by a tether are planned for study using the MDCA. Such research supports how liquid-fuel-droplets ignite, spread, and extinguish under quiescent microgravity conditions. This understanding will help us develop more efficient energy production and propulsion systems on Earth and in space, deal better with combustion generated pollution, and address fire hazards associated with using liquid combustibles on Earth and in space.

As a result of the concurrent design process of MDCA and CIR, the MDCA team continues to work closely with the CIR team, developing Integration Agreements and an Interface Control Document during preliminary integration activities. Integrated testing of hardware and software systems will occur at the Engineering Model and Flight Model phases. Because the engineering model is a high fidelity unit, it will be upgraded to a flight equivalent Ground Integration Unit (GIU) when the engineering model phase is completed. The GIU will be available on the ground for troubleshooting of any on-orbit problems. Integrated verification testing will be conducted with the MDCA flight unit and the CIR flight unit. Upon successful testing, the MDCA will be shipped to the Kennedy Space Center for a post-shipment checkout and final turn-over to CIR for

final processing and launch to the International Space Station.

### MDCA/CIR Testing and Integration

Integrated testing between the MDCA hardware and CIR carrier will be performed on the Engineering Model (EM) of both pieces of hardware. Both units are hi-fidelity, flight-like units. Testing, planned for December 2002 will include a full array of sub-package testing, leading to a full end-to-end EM integrated test. Upon completion, the MDCA EM unit will undergo vibration & microgravity testing, EMI/EMC, and acoustical testing. In parallel with EM environmental testing, the MDCA flight hardware will be procured and assembled. Testing will be conducted on the flight unit in early summer 2003 in preparation for a turn-over of the hardware to CIR for flight integrated testing in August 2003.

### Launch of the MDCA Hardware

The MDCA hardware will be launched as stowed hardware on the same flight as the CIR. This hardware will include the MDCA common hardware and experiment unique hardware for the first two droplet investigations, Droplet Combustion Experiment -2 (DCE-2) and Bi-Component Droplet Combustion Experiment (BCDCE). The Chamber Insert Assembly, MDCA Avionics Package, and experiment unique hardware will be separate stowed items. Once on-orbit, the CIA and Avionics Package will be removed from stowage. The avionics package will be installed on the CIR rack and the CIA will be inserted into the CIR combustion chamber. Experiment unique diagnostics for the first experiment, DCE-2, will be installed on the CIR optics bench. Once the configuration is complete CIR/MDCA are ready for operation.

### MDCA Operations

Once on-orbit, the MDCA is managed from the GRC Telescience Support Center (TSC). The MDCA operations team resides at the TSC. Data is transmitted to the PI's at their home sites by means of TReK<sup>10</sup> workstations, allowing direct interaction between the PI and operations staff to maximum science. Upon completion of a PI's experiment, the MDCA is reconfigured for the next of the three follow-on experiments or ultimately removed from the CIR, placed into stowage, and returned to Earth.

### MDCA Subsystems

The MDCA CIA provides all necessary hardware and interfaces to perform PI science on one platform. Most experimental functions occur within the CIA structure. The CIA consists of two major components: an Experimental Mounting Structure (EMS) and an Internal Apparatus (IA). The EMS

provides the main structure for the CIA and acts as the primary mechanical interface with the CIR combustion chamber. It consists of two endplates, support structure and removable shrouds to protect the IA during crew activity. The IA provides the primary mounting platform for all experiment specific hardware and functions to include droplet dispensing, deployment, and ignition. The IA encompasses all motors used for the operation of the experiment, a water-cooled system, radiometers, and an internally mounted color camera. The IA also provides for future add-on hardware for follow-on PI's. The Chamber Insert Assembly is shown in Figure 6.

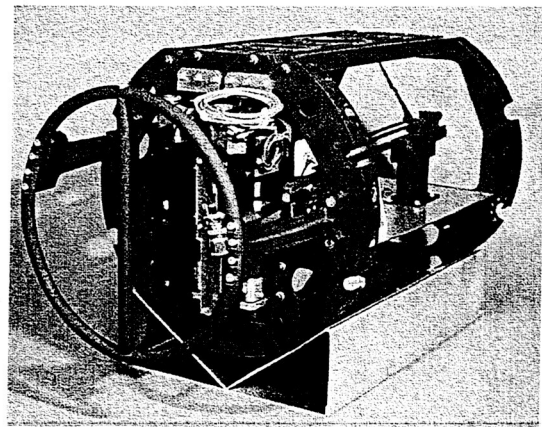


Figure 6. Chamber Insert Assembly

Other subsystems on the CIA include the Droplet Dispensing System, Droplet Deployment System, Fiber Support System and Ignition System. There are two independent replaceable dispenser systems on the IA. Each system consists of a motor housing, replaceable fuel reservoir filled with the PI specific fuel, and fuel isolation valve. Flexible tubing connects the fuel system to the deployment needles. Fuel is dispensed by means of a lead screw on the motor, which in turn pushes the plunger on the syringe. The Dispensing System is shown in Figure 7.

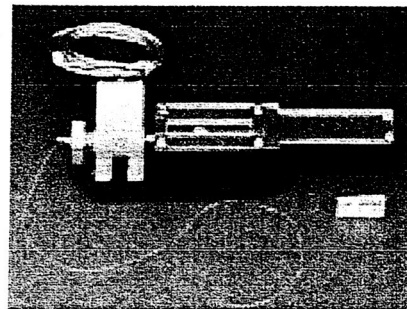


Figure 7. MDCA Dispensing System

The Droplet Deployment System consists of two independent replaceable deployment needles made of 0.010 inch outer diameter stainless steel tubing supported by a ceramic sleeve. Each needle is bent 90 and flared at the end to aid in droplet deployment. The needles are mounted to individual rotary servomotors that rotate the needles to a predetermined location, creating a minimal gap between the tips. Fuel is metered to the end of the needle tip forming a droplet of precise volume. The droplet then centers itself between the two needles. The needles are rapidly accelerated apart, deploying the droplet off the needle tips. The rapid acceleration leaves the droplet in place with minimal to no residual motion. See Figure 8 for a pictorial depiction of the Droplet Deployment System.

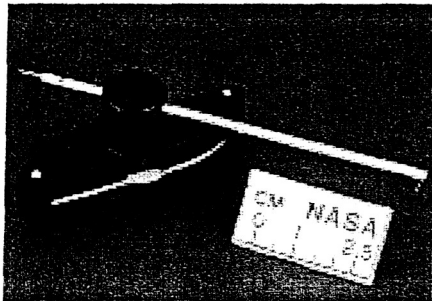


Figure 8. Droplet Deployment System

The Fiber Support System consists of a replaceable Retractable Indexing Fiber (RIF) mechanism, 229 mm long, supporting a 79micron diameter silicon carbonitride fiber fastened between two support arms with epoxy to a tension of 3000 psi. The RIF assembly allows for the fuel droplet to be deployed onto, and thus tethered to, the fiber during experimental burn and observation. When used, the fiber is rotated 200 deg into the deployment area by means of a rotary stepper gear motor. The RIF also translates along its axis, to provide a clean portion of the fiber for successive experimental tests. See Figure 9.

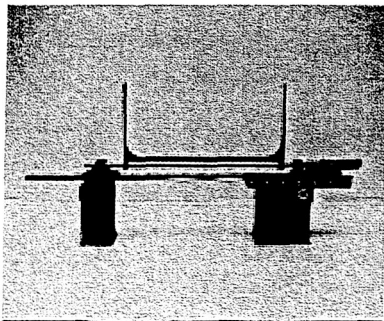


Figure 9. Retractable Indexing Fiber

The Ignition System consists of two independent replaceable hot wire igniters opposed 180 deg, controlled by individual actuators. The ignition wires are 4mm diameter loops of Kanthal A-1 wire, 30 AWG (American Wire Gauge). Each loop is mounted to a ceramic structure. The assembly is fully replaceable. The ceramic igniter sleeve has two pins that mate with two sockets on the igniter-mounting interface. This interface is fixed to the igniter motors. These motors move the igniters into the deployment area in precise linear steps and then quickly retract the igniters after ignition. The Ignition System is shown in Figure 10.

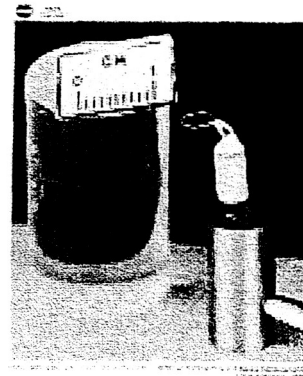


Figure 10. MDCA Ignition System

### Avionics

The Avionics Package provides the processing and control interface hardware for controlling the MDCA and communicating with the CIR hardware. The avionics controls the CIA motors, provides the functions for input and output data control, and is the source for experimental data collection. The package will receive electrical power at 28 VDC from the CIR. DC-DC converters within the avionics will convert the voltage necessary for MDCA operation. The package will acquire health and status data from the CIA via dedicated input/output lines. The data will be downloaded to the CIR Input/Output Processor (IOP) via the CIR Ethernet for downlink. MDCA commands will be uplinked from the ground to the IOP, or issued from a Station Support Computer (SSC) to the IOP. The IOP will transmit the commands to the avionics package via the CIR Ethernet. The enclosure of the avionics package will provide the Electromagnetic Interference (EMI) shielding and provide the grounding to the CIR optics bench. See Figure 11.



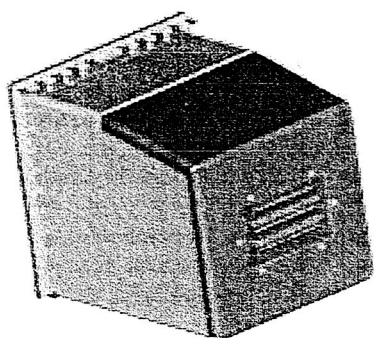


Figure 11. MDCA Avionics Enclosure

### Diagnostics

The majority of diagnostic hardware will be CIR provided with some elements provided by MDCA. The diagnostics hardware selection and configuration is specific to each experiment: DCE-2, BCDCE, SEDC, and DDCE.

CIR provided diagnostics hardware for MDCA includes:

- High Bit Depth/Multi-Spectral Imaging Package (HiBMs)
- High Frame Rate/High Resolution Camera (HFR/HR)
- Low Light Level Packages (UV and IR)
- Illumination Package

MDCA provided diagnostics hardware includes:

- Color Camera – mounted on the CIA providing enhanced color imaging of combustion experiments.
- Radiometers – mounted on the CIA providing measurement of radiation during combustion.
- Illumination/Particle Imaging Velocimetry Package – mounted on the CIR optics bench providing measurements of the droplet's internal flow velocities.

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